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GAN-based Fine-tuning of Vibrotactile Signals to Render Material Surfaces

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ABSTRACT The design productivity of fine-tuning for vibrotactile stimuli becomes important as consumer devices equipped with vibrotactile actuators will become wide-spread. The fine-tuned vibrotactile stimuli output by vibrotactile actuators allows the end-users to feel the surface of the virtual material. However, there is no suitable tool for fine-tuning while there are existing tools suitable for initial designing. In this paper, we test whether we can use GAN (Generative Adversarial Network)-based vibrotactile signal generator at the tuning phase. The generator provides a material-level interface to designers. Designers can define any intermediate materials among pre-defined 108 materials and obtain corresponding intermediate signals that the generator generates. We showed the applicability of the generator to the fine-tuning of vibrotactile signals from the viewpoints of principal component analysis and a user test.

INDEX TERMS Human computer interaction, Design tools, Haptic interfaces

I. INTRODUCTION

RECENTLY, consumer devices equipped with vibrotactile actuators such as Apple Watch [1] or Pebble watch [2] have become wide-spread. For example, there are touch pens, touchpads, and game controllers with vibrotactile actuators around us, and we think of them as nothing special [3]. Vibrotactile stimulation allows humans to perceive the material properties of virtual surfaces [4]–[7]. If vibrotactile stimuli match the material attributes of visualized surfaces in the application, the users perceive the textures as more realistic [7]. Thus, tactile designers need to design vibrations carefully and how to design the vibrotactile stimuli is becoming essential.

The vibrotactile design process consists of preparation, initial designing, and fine-tuning. It is known that the fine-tuning phase occupies more than half of all workloads [8]. Thus, improving productivity in the fine-tuning phase will contribute to the improvement of all workloads. However, there is no suitable tool for iteration and refinement while there are existing tools for preparation and initial designing [9], [10]. The difficulty in fine-tuning exists in the control of high-level material parameters such as rocky or metallic by changing low-level engineering parameters such as frequency or amplitude [11]. The ability to use low-level engineering parameters to construct or evaluate for material characteristics is tacit knowledge that vibrotactile designers build over the years.

Based on these considerations, we set a goal of this study as providing a vibrotactile design method that enables non-expert designers to fine-tune vibrations with material-level user-interfaces. This study utilizes the Generative Adversarial Network (GAN) based vibration generator introduced in a previous study [12].

At the phase of fine-tuning of the vibrotactile signals using the generator, we assumed the following scenario. When designers would like to obtain the vibration of intermediate materials of the aluminum board and wooden board, designers feed interpolated material attributes of the aluminum board and wooden board into the generator. They get generated vibrations. However, the generated vibrations do not satisfy the designers' demands. In such a case, designers slightly modify the interpolation ratio of material attributes and they try a newly generated vibration.

Thus, in this study, we test whether the model allows designers to synthesize intermediate vibrations by configuring the interpolation ratio of the material attributes. We evaluated the generated signals from the interpolated material attributes in both objective and subjective evaluations. The results of the evaluations showed that the model provides a fine-tunability of vibrotactile signals for designers.

II. RELATED WORK

A. EXISTING VIBROTACTILE DESIGNING TOOL

1) Direct Playback of Recorded Vibrotactile Signal

The most simple design method is to record and replay the scanned acceleration signals [13]–[15] of the material surfaces. In this method, designers record raw signals with microphones or acceleration sensors while they touch the surface of the material. TECHTILE toolkit and Stereohaptics provided recording devices that can be easily accessed by designers [13], [14]. They held workshops where non-professional people were encouraged to work with vibrotactile recording and replaying experience. Seteohaptics [15] adopted the same approach as the TECHTILE toolkit. They utilized the left and right audio channels and designed two vibrations at once. Since these studies recorded the actual vibration occurred at the contact surface of the material, replaying the recorded signals can give users high realism through the vibration. The disadvantages of this design method are that it is time-consuming and has little flexibility. Because the designers need to prepare the material at hand, it takes much time to record vibrations. In addition, if the recorded vibrations do not satisfy the requirements a little, the designers need to find similar but different material surfaces to fine-tune the vibrations.

Recently, open datasets which are a collection of vibrotactile signals have appeared [16]–[19]. Designers can obtain 100 kinds of texture vibrations from The Penn Haptic Texture Toolkit [16], which is based on the recorded data. The LMT haptic texture database [17] provides recorded vibrations of 108 different materials. By utilizing these open vibrotactile datasets, designers do not need to prepare actual materials and recording systems themselves. However, the current datasets contain vibrations of up to hundreds of materials, though there exist unlimited kinds of materials in the real world. Therefore, it is difficult to find the appropriate vibrotactile signals from the datasets currently.

2) Vibrotactile Authoring Tool

With their crucial role in the vibrotactile design process, authoring tools have received increasing attention in recent years. Existing tools are built around the most important design parameters and approaches identified in the literature or by practitioners. Such tools use graphical, mathematical representations to edit the characteristics of the wave, including the amplitude, frequency, and duration of tactile sequences [9], [10], [20]–[22]. For example, a web-based system [21] is an opportunity to edit and observe the effect of high availability. These studies provided a low-level, simple waveform timeline interface for combining them into vibrotactile patterns. However, it is difficult to express a high-level material impression using the combination of simply patterned waveforms. Therefore, it is not easy for designers to design vibrations that give users high-realism of material properties.

B. GENERATIVE ADVERSARIAL NETWORK

GANs [23] is a popular generative framework that can be used to generate new samples. GANs framework is mostly used for generating realistic samples of natural images. In this study, we use the GANs framework to generate sharp time-frequency samples for vibrotactile feedback. Specifically, generating the vibrotactile samples from materials attributes is our goal. Such the cross-modal generation using GANs has been studied recently. Text to image generation was realized by [24]. In their studies, plausible images for birds and flowers were generated from their text descriptions. Cross-modal audio-visual generation was studied in [25]. Though they tried to generate a spectrogram convertible to sound from video frames, they generated the rough spectrogram, which was not convertible to good sound. The reason for the poor generation was that even the recent GANs couldn't generate the image covering a broad frequency range such as 44100 Hz in the audio data. In contrast, the frequency range needed for vibrotactile stimuli is smaller than audio stimuli, and thus GANs could cover the frequency range or vibrotactile signals that is enough for human mechanoreceptors.

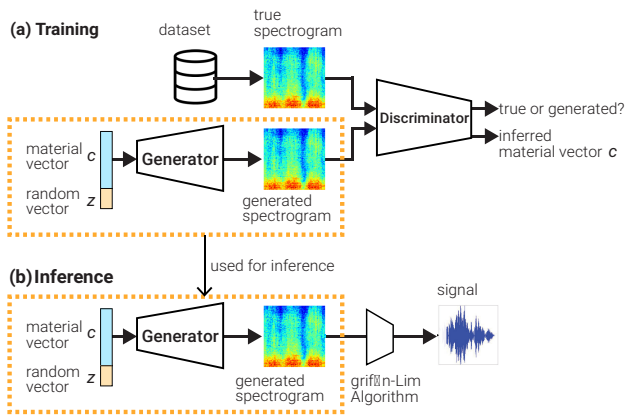

FIGURE 1. Top(a): Generator and discriminator are connected during the training phase. Bottom(b): Generator architecture during inference phase. Only the generator is used for the inference phase.

Thus, we have constructed the vibrotactile signal generator based on GANs. The designers can obtain the corresponding signals by feeding the material vectors into the generator. The previous study [12] demonstrated the concept of a training model that can generate vibrotactile signals. The output of the generator is vibration and it is an acceleration signal (shown in Fig.1). The input to the generator is the material vector c representing the material attributes of the vibrotactile signal. The material vector indicating the attribute of the material is, for example, $(c_{timber_A}, c_{metal_B}, c_{fabric_C}, \cdots) = (1.0, 0, 0.0, \cdots)$, $(c_{timber_A}, c_{metal_B}, c_{fabric_C}, \cdots) = (0.3, 0, 0.1, \cdots)$, and so on.

The dimensions of the material vector are 108, and thus designers can designate vector in the 108 material dimensions. However, whether the model can generate the intermediate

signals from multiple materials has not been clarified yet. Thus, this study evaluates the capability of the model at the fine-tuning phase to provide intermediate signals as follows:

- In section III, we clarify whether the model can generate signals monotonically and continuously with regard to the transition of the material vector by means of the Principal Component Analysis (PCA).
- In section IV, we conduct a user study to clarify whether the user feels the monotonous change in the material feeling of vibration when the input material vector is finely and monotonously changed.

III. OBSERVATION OF GENERATED, INTERMEDIATE VIBRATION USING PCA

At the fine-tuning phase, designers slightly change the interpolated material vector and feed them into our generator. The generator is required to generate the corresponding continuously changed vibrotactile signals according to the changed material vector. In this observation, we assumed the simplest case where designers use the interpolated material vector $c_{interpolation}$ between the material vectors c_1 and c_2 representing two different specific materials.

$$c_{interpolation} = c_1 \cdot (1 - \alpha) + c_2 \cdot \alpha \tag{1}$$

For example, when designers would like to get a vibration intermediate between that for materials "Jeans" and "Aluminum", they synthesized a material vector by mixing c_{Jeans} and $c_{Aluminum}$ and fed this into the generator. Then, designers slightly change the α to fine-tune the intermediate vibration. We verify the vibration generated in that case.

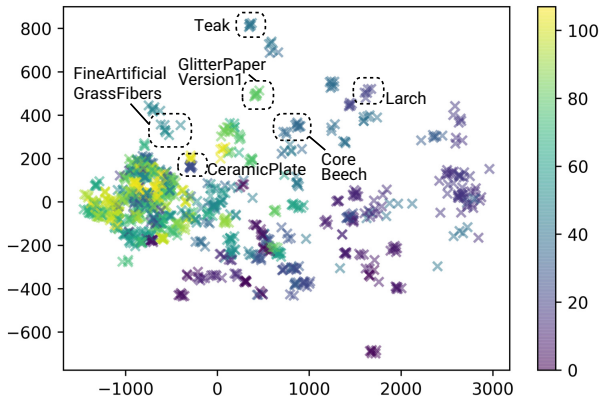

FIGURE 2. Results of the principle analysis.

Then, we use PCA over spectrograms to observe the generated, intermediate vibrotactile signals in comparison with the vibrotactile signals corresponding to specific materials. Based on the fact the human vibrotactile sense depends on specific frequency ranges and on the fact that the PCA over spectrogram shows a variable representative of the frequency domain, the PCA will provide meaningful insights for the intermediate vibrotactile signals. The PCA results for the vibration generated for each of 108 materials are shown in Fig.2. Vibrations generated from material vectors directly representing 108 different materials are plotted in different colors. The horizontal axis corresponds to the first principle component and the vertical axis represents the second principle component. The figure shows the distance between the generated vibrations. For example, the generated signal of "Teak" material is different from those of other materials in these two main components.

In order to qualitatively evaluate the fine-tunability, we selected some pairs of materials to use their material vectors as c_1 and c_2. We selected "Teak" as a material of c_1 and five other materials of c_2, the material names of which are shown in Fig.2. The reason for the selection of these materials is because their positional relations were clear in the PCA. The generated signals corresponding to six materials are shown in Fig.2.

We visualize the intermediate spectrograms that are generated based on interpolated material vectors in Fig.3. The leftmost column shows the generated spectrogram based on $c = c_1 = c_{Teak}$. The rightmost column shows the spectrogram generated when $c = c_2$. The middle columns shows the spectrogram generated when c is intermediate between c_1 and c_2.

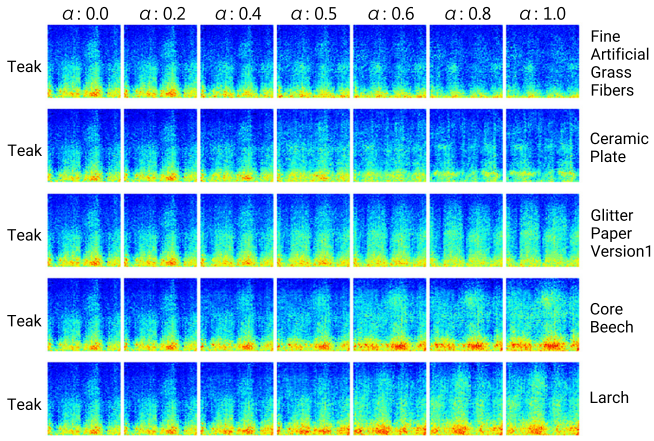

FIGURE 3. Spectrograms generated from intermediate material vectors.

We mapped the generated spectrogram when c was interpolated between c_{Teak} and c_2 onto the previous PCA 2-dimensional spaces (Fig.4). α is changed from zero to one by 0.05 interval and thus, there are 200 generated spectrograms for each pair of c_{Teak} and c_2. The intermediate spectrograms are colored in blue at the point of "Teak" when α is zero and $c = c_{Teak}$. They are colored in red when α is one and $c = c_2$. The continuous transition from blue to red shows the continuous transition of the generated, intermediate signals as α increases.

Summarizing the observation, with regard to the first and second main components of PCA, it is shown that the generated, intermediate signal has an intermediate characteristic between c_1 and c_2. In addition, because the point in blue

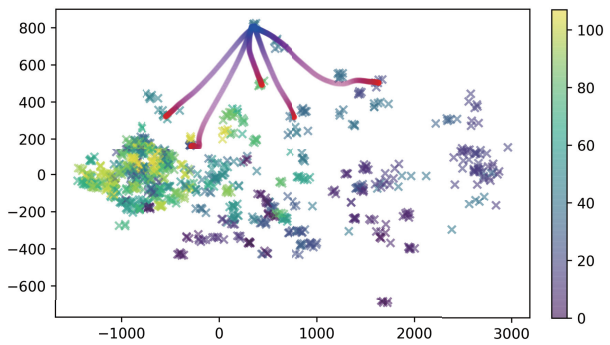

FIGURE 4. Spectrograms generated from intermediate material vectors are mapped on the PCA two-dimensional spaces.

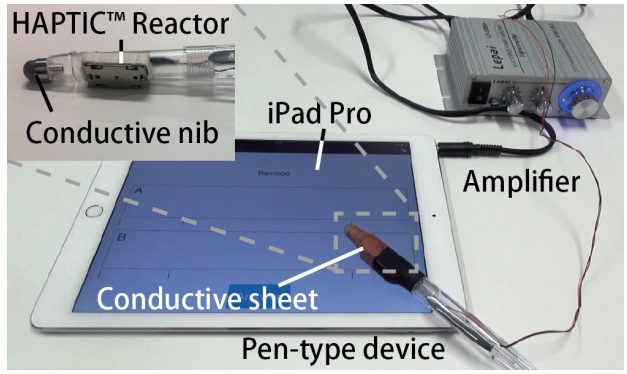

FIGURE 5. Setup of the experimental system.

changes to the point in red continuously, the generated vibrations are shown to be distributed continuously. This shows that designers can tune the vibration by changing the material vectors.

IV. USER STUDY

We conducted the user study to test whether our generator could provide the fine tunability of generated vibrotactile signals from a perceptual point of view. The number of participants was ten (eight males and two females) and were aged from 22 to 25 years. All the participants were right-handed. None of them reported a history of neurological, psychiatric or other diseases that could have interfered with tactile sensitivity. The University of Tokyo Ethics committee (approbation number: KE17-63) approved the data acquisition in this paper and written informed consent was obtained from all participants.

A. EXPERIMENTAL SYSTEM

The participant task in this user study was to move a pen-type device on the surface of a tablet screen while receiving vibrotactile feedback via the pen. Our experimental system included a tablet device (Apple Inc., iPad Pro 9.7 inch), a signal amplifier (Lepai Inc., LP-2020A), and a pen-type device with a vibrator (Fig.5). The tablet device's screen refresh rate was 60 Hz, and the touch position acquisition was performed at 100 Hz. Although no formal data were obtained on the accuracy of the contact position acquisition, the resolution was 264 ppi and the contact position was acquired every 1 pixel; hence, it is assumed that the acquisition accuracy is about 0.1 mm. The pen-type device is specifically described in the next paragraph.

The pen device was approximately 140 mm long and the weight of it was approximately 20 g. The diameter of the grip part of the pen was approximately 10 mm. We covered the pen tip with a conductive material that is ordinarily used for the stylus. Because the shaft of the pen was plastic and does not conduct to the grip part, we wound a conductive sheet on the grip to react with a capacitance-type touch screen. We embedded the vibrator (ALPS Inc., HAPTIC Reactor Hybrid Tough Type [26]) inside the pen-type device at a position 2 cm from the end of the pen where the participants gripped it. The vibrator was small (35.0×5.0×7.5 mm) and light (approximately 5 g) enough that participants would not tire from moving the pen.

When participants moved the pen on the surface, the vibration signal was emitted from the earphone jack of the tablet. The amplifier amplified the signal and the vibrator embedded in the pen presented the vibration to the participants' fingers.

B. VIBRATION PRESENTED TO PARTICIPANTS

To apply the evaluation result of the user study to materials as diverse as possible, we selected four pairs of base materials based on four different points of view. We assumed that the base materials were either 1) the same material, 2) similar materials, 3) not similar materials but intermediate material is familiar to users, or 4) totally different materials for which intermediate material does not exist. The four viewpoints have differences in the similarity between materials or the probability of presence in the real world of the intermediate materials between the two. We used pairs of material vectors c_1 and c_2 of the base materials and synthesized the intermediate material vector c using equation (1). The four pairs of base materials selected were as follows:

1) c_1: "Squared Aluminum Mesh", c_2: "Aluminum Plate" (Same materials but different local geometry)
2) c_1: "Carpets", c_2: "Jeans" (Similar materials)
3) c_1: "Aluminum Plate", c_2: "Granite Type Veneziano" (Not Similar materials)
4) c_1: "Jeans", c_2: "Granite Type Veneziano" (Totally different materials for which intermediate material does not exist)

The difference between 3) and 4) is the probability of the presence of intermediate materials. The intermediate materials between "Aluminum Plate" and "Granite Type Veneziano" can be present as an alloy or ore mineral. In contrast, the mixture between "Jeans" and "Granite Type Veneziano" never be present.

We synthesized variations of the material vector c by

setting α at 0.0, 0.2, 0.4, 0.5, 0.6, 0.8, and 1.0. When α was close to zero, the material vector c was close to c_1. When α was close to one, the material vector c was close to c_2.

C. TASK DESIGN

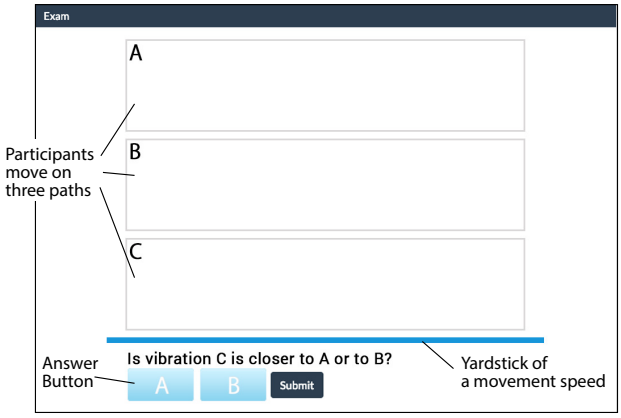

FIGURE 6. Experimental window.

This study used a within-participants design. Participants could move the pen-type device along the three different predefined paths displayed on the screen. The experimental window is shown in Fig.6. On the first path, participants felt vibrations generated from the material vector c_1 or c_2. On the second path, they felt vibrations generated from the material vector c_1 or c_2. When vibrations from c_1 were set on the first path, vibrations from c_2 were set on the second path. When the vibrations from c_1 were set on the second path, the vibrations from c_2 were set on the first path. On the third path, they felt vibrations generated from the interpolated material vector c. The task assigned to the participant was to judge whether the intermediate generated vibration on the third path from the material vector c was similar to the vibrations on the first or second path.

In the following paragraph, we describe the procedure of the participants' task in one trial. The participants moved the pen on a predefined path from left to right for about 100 mm distance at a fixed speed with their dominant hand. The touchscreen visualized a bar that indicated at what speed to move the pen in order to control the movement speed. Participants moved the pen over a distance of approximately 100 mm in 1.6 seconds, which is what the bar elongation instructed the participants to do. Participants were asked to grip the pen with their fingers at the position where the vibrator was embedded so that they could feel the vibration with their fingers. They answered which generated vibration (i.e., on the first or second path) was similar to the intermediate generated vibration on the third path. They tapped one of the two answer buttons visualized at the bottom of the screen.

For each of four pairs, participants judged the seven intermediate vibrations (α is 0.0, 0.2, 0.4, 0.5, 0.6, 0.8, and 1.0) and they judged each intermediate vibration seven times. Thus, each participant did 196 (= 4 $\times$ 7 $\times$ 7) trials in total. To prevent sequential effects, the presentation order of the intermediate vibrations was randomly assigned and counterbalanced across participants. Also, the assignment of c_1 and c_2 for the first and second paths is randomized.

D. RESULTS

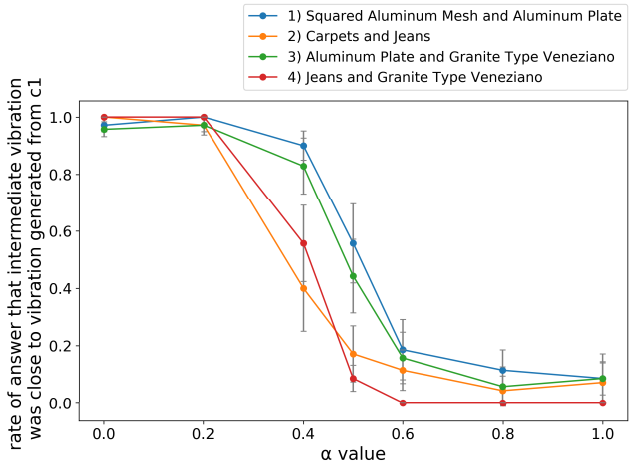

FIGURE 7. Percentage of answers that said the intermediate vibration was close to the vibration generated from the material vector c_1. The error bar represents the standard error computed from the average percentage of participants.

Fig.7 shows the percentage of participants' answers saying that the intermediate vibration was close to the vibration generated from the material vector c_1. The percentage changed monotonically according to the configuration of α for all pairs.

One of the free comments from participants said that the texture felt much different from the glass surfaces of the touchscreen.

E. DISCUSSION

For all pairs (1–4), the percentage of answers seems to transition monotonically. This means that the generated intermediate vibrations from two different materials can be controlled by the α value. Let us assume the cases when the tactile designers generate the intermediate vibration from a certain base materials "A" and "B" by defining the α value. After setting the α at 0.5, if designers try the generated vibration and would like to obtain a generated vibration close to material "A", they should set α to a smaller value such as 0.4. When they would like to obtain the generated vibration close to material "B", they should set α to a larger value such as 0.6.

Although the monotonicity of the curve in Fig.7 is the same, the points of subjective equality between c_1 and c_2 were biased for the pairs of 2) "Carpets" and "Jeans" and 4) "Jeans" and "Granite Type Veneziano". In other words, the α values corresponding to the rate of 0.5 are different among pairs.

The reason for the bias for the pair of 2) "Carpet" and "Jeans" is thought to be that it was difficult for participants to

imagine the surface vibration of "Carpet" rather than "Jeans". Therefore, it seems that participants tended to choose "Jeans" when α was 0.5.

The reason for the bias for the pair of 4) "Jeans" and "Granite Type Veneziano" is thought to be the difference in the vibration characteristics for each material. The "Granite Type Veneziano" was rocky type material and it had specific characteristics in lower frequency ranges. This seemed to make it more frequent for the participants to select "Granite Type Veneziano" when they felt the vibration in the low-frequency range. In contrast, the "Jeans" had little characteristics on specific frequency ranges and it seemed to make it less frequent for the participants to select "Jeans" than "Granite Type Veneziano". This leads to the bias of the point of subjective equality for the pair.

These suggest that the value of α does not uniquely determine the subjective ratings on the intermediate vibrations among multiple materials. Thus, the process of tuning of α repeatedly is still needed. However, the low-level design of parameters such as frequency or amplitude is no longer necessary with our generator. The designers do not need to care for those low-level design but only care for the material-level attribute design. This leads to improved productivity for each iterative process.

V. CONCLUSIONS

This study evaluates the capability of the GAN-based model to provide intermediate signals and it can be used during fine-tuning. The model hides the low-level engineering parameters such as frequency and provides designers material-level user interface. Thus, non-expert designers can use the model.

The summarization of the evaluation is as follows:

- We clarified that the model can generate signals monotonically and continuously with regard to the transition of material vector by means of the PCA.
- The user study clarified that the user feels the monotonous change in the material feeling of generated vibration when the input material vector is finely and monotonously changed.

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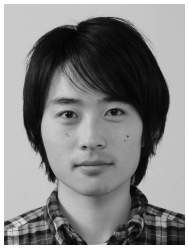

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